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Toxicity, Fire Hazard and Upholstered Furniture

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ABSTRACT

Fire fatalities associated with upholstered furniture fires commonly involve the toxic effects of fire gases. Extensive results, however, both from experiments and from modeling, are presented in this paper that demonstrate that occupant life safety can only by ensured by assuring that furniture fires do not reach a high heat release rate. Differences among commercial products associated with toxicity effects are not significant. A very remote possibility exists that someone could produce furniture having combustion products' toxicity significantly greater than exists in the present marketplace. A combustion toxicity test does exist which would allow the accurate screening out of such products. Any usable combustion toxicity test method requires the use of test animals; no non-animal-based test is possible which can successfully identify products of unusual or extreme toxicity.

Keywords: combustion products; fire hazard analysis; fire toxicity; heat release rate; toxic potency; upholstered furniture.

INTRODUCTION

In this paper, we will examine the relative importance of the heat and the toxicity factors in contributing towards occupant endangerment in the room of fire origin. Such information can help form the basis for future, more detailed engineering studies. Smoke opacity aspects will also have to be examined in parallel, but this is outside of the scope of this paper.

HEAT RELEASE RATE

A few years ago the National Institute of Standards and Technology (NIST) performed a study specifically designed to compare the relative importance of heat release rate (HRR) to other factors influencing the fire outcome [1]. Furniture fire behavior was cited as a situation illustrating the preponderant importance of the HRR. An example was presented based upon a case where an upholstered chair was burning in a room with a single doorway opening. The procedures of HAZARD 1 [2],[3] were used to calculate the outcomes for several scenarios. To assess the relative importance of several factors, the following variations were studied:

- base case, single burning chair in room,
- doubling the heat release rate of chair,
- doubling the toxicity of materials
- halving the ignition delay of burning chair from 70 s to 35 s.

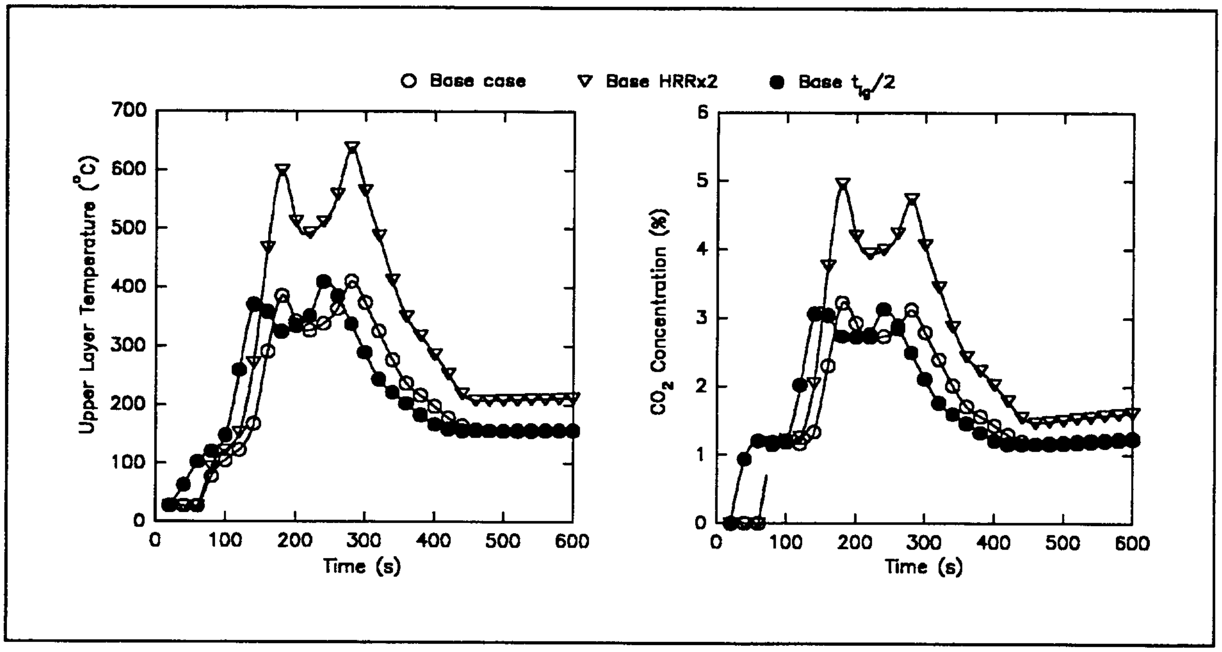

Figure 1. Results of simulations with HAZARD I

The general development of these fires is shown in Figure 1, where the predicted temperatures and CO_2 levels in the upper layer of the room are given. CO_2, rather than CO, was plotted since the development of the theory for CO production (discussed below) was still in progress at the time. As expected, changing the heat release rate has a much greater effect than changing the ignition time. The relative effect of changes in the toxicity can be seen in Table 1, as calculated from the simulations illustrated in Fig. 1.

Comparing the results for the four scenarios, it is apparent from the predicted time to death that *changing the heat release rate has by far the greatest effect on the tenability* of the space, reducing the time to death from greater than 600 s (the total simulation time) to about the same time as the time to incapacitation for all other scenarios. Additional details are given in reference [1] and in a newly-published book on the topic of HRR [4].

Table 1

Scenario	Time to incapacitation (s)	Time to death (s)
Base case	180	>600
Double heat release rate	160	180
Double material toxicity	180	>600
Halve ignition delay	140	>600

CAUSE OF DEATH

In another NIST study, computer fire modeling was done of the fire conditions in the initial room of fire origin [5]. In this case, the fire source was not specifically limited to an upholstered chair, but was, rather, of a generic type: 'slow,' 'medium,' and 'fast' fires. The purpose was to compare whether the thermal effects or those of toxicity would first lead to untenable conditions, using the tenability conditions built into HAZARD 1. These include a temperature limit of 100°C and a toxicity limit expressed as concentration-time product of 900 $g{\cdot}min{\cdot}m^{-3}$. The results are shown in Fig. 2.

The results of Fig. 2 show that even for the worst case (the 'slow' fire), by the time that untenable thermal conditions have been reached, the fire conditions are still a very long ways from reaching the assumed untenable concentration-time value of 900 $g{\cdot}min{\cdot}m^{-3}$. The value of 900 $g{\cdot}min{\cdot}m^{-3}$ comes from using a typical toxic potency value of 30 $g{\cdot}m^{-3}$, which is applicable when occurring over an exposure time of 30 min; thus $30 \times 30 = 900$ $g{\cdot}min{\cdot}m^{-3}$. The results of Fig. 2 show that for thermal and toxic incapacitation effects to occur simultaneously in the room of fire origin, the chair would have a toxic Ct product equal to about 16 $g{\cdot}min{\cdot}m^{-3}$; for a 30 min exposure this would require a chair LC_{50} value[b] of about 0.5 $g{\cdot}m^{-3}$. Such a very high value of toxic potency is, as is discussed below, exceedingly uncommon. For toxic effects to predominate and not merely be equal to the thermal ones, the product LC_{50} values would have to be even smaller.

We may note that such computations are not merely hypothetical—they are also verified by experimental work. In a parallel NIST investigation [6] real-scale fires were conducted in a burn room and animal deaths were monitored. It was found that prior to flashover, room fires simply did not generate gas mixtures toxic enough to kill test animals. When flashover occurs, of course, thermal conditions of tenability in the room have already been well exceeded, and temperatures have risen to *ca.* 600°C.

The above effects all were considered to be occurring within the room of fire origin, consistent with the expectations of the Second Essential Requirement. In the United States, the focus of fire hazard research has been more on conditions leading to fire deaths away from the room of fire origin. This is because U.S. fire statistics [7],[8] show that 69% of all fire deaths are associated with post-flashover fires, with the vast majority of deaths occurring outside the room of fire origin. Such statistics are,

[b] Note that *lower* numerical values of LC_{50} mean *greater* toxicity.

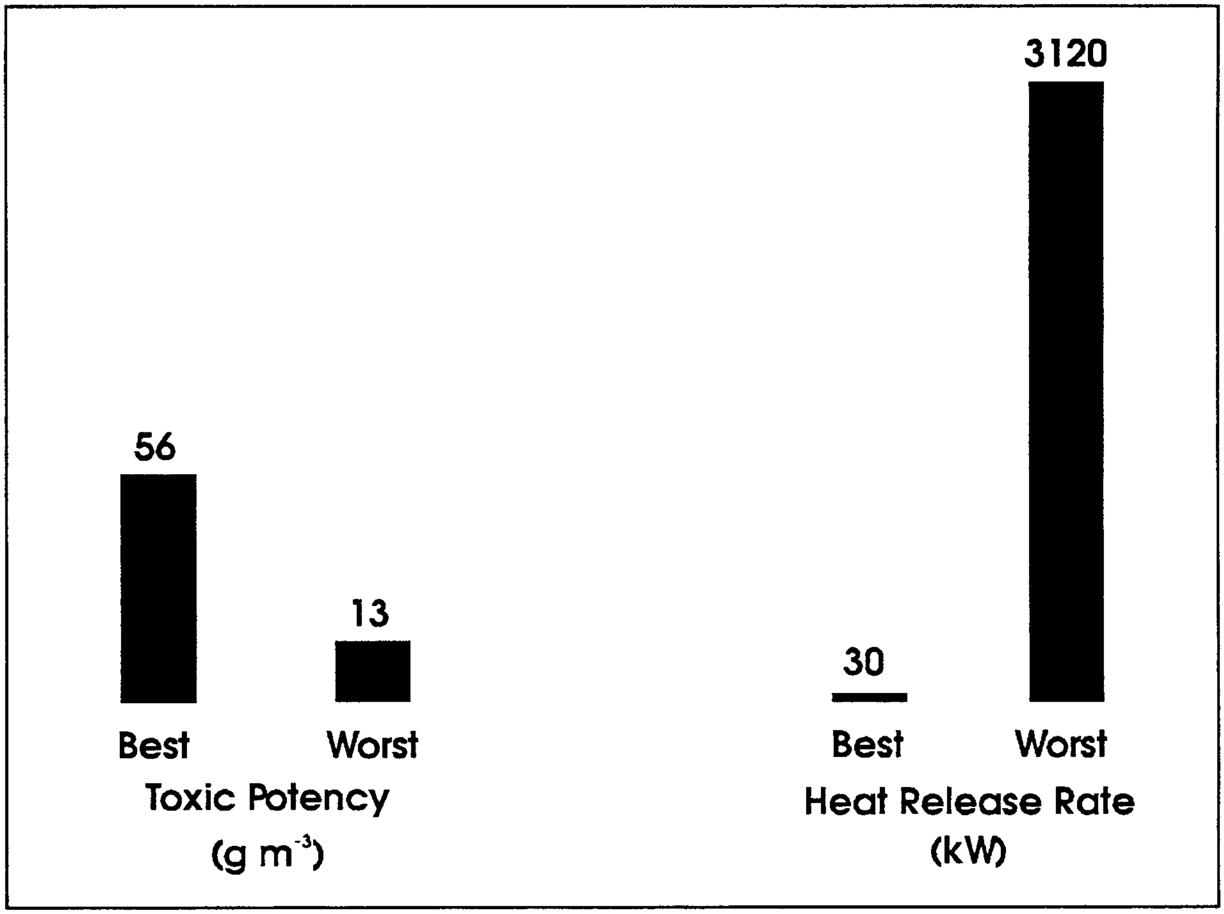

Figure 3 Comparison between actual product HRR range versus toxic potency range

For toxicity testing there had, of course, been no shortage of bench-scale methods proposed and, to some extent, utilized in various laboratories. Many of these had serious problems with the design of their combustion systems or with the toxicological assessment procedures. It is felt that the extensive work leading to the new proposed method was able to overcome such difficulties. More important, for none of the earlier methods was there any adequate assurance that the bench-scale results adequately described the real-scale reality, *i.e.*, validation was lacking. For the new radiant toxicity test method two extensive studies were conducted [6],[12]. These successfully demonstrate that the new method can be used to predict toxicity in real-scale fires.

Full details are given in [5]; here we will merely summarize the overall features. The method uses gas analysis for the principal toxic products in order to minimize the use of animals. An estimate of the LC_{50} value is initially obtained through analysis of the several common fire toxicity gases. The final step of the procedure is, necessarily, either a confirmation by animal testing that the analytically-based LC_{50} estimate is correct, or else, a complete animal-based experimental redetermination of the actual LC_{50}, if needed. This procedure is considered to be the only one that is worth performing. For the benefit of audiences from the countries where use of animals in toxicity testing is essentially precluded, we must explain the situation.

Studies at NIST and examination of other literature throughout many years of work have shown that no product was ever found which was abnormally toxic (say a factor of 100 worse than the 'typical' raw LC_{50} value of 30 $g \cdot m^{-3}$) due to an exceedingly high production of the common, measurable combustion gases. Such commonly monitored gases include CO, CO_2, HCl, HCN, HBr, and reduced oxygen. Reports of 'supertoxic' combustion products have, in general, been extraordinarily rare and have typically been for laboratory curiosities, not for commercial products. Nonetheless, when such reports have been noted, the extreme toxicity has invariably been seen to be from a rare combustion product. An example was a 1975 report on a laboratory formulation of a non-commercial rigid polyurethane foam, where extreme toxicity was attributed to the formation of a bicyclic phosphate ester, namely, 4-ethyl-1-phospha-2,6,7-trioxabicyclo[2,2,2]octane-1-oxide [13]. Needless to say, this toxic agent is not one for which normal analytical procedures are in place. Even if they were set up for this one rare compound, thousands of other similarly rare yet extremely toxic compounds can, in principle, be generated.

We see, thus, that the only combustion products found to generate *extreme* toxicity are those which are also of *unusual* toxicity; the normal, regularly-measured ('usual') combustion products are neither toxic enough nor are produced in such abundances as to exceed the experimentally observed 4:1 range of product toxicities. Thus, we can conclude that there is no feasible analytic-only procedure which can adequately measure *any* of the potential products of extreme toxicity. This means that an analytic-only approach to fire toxicity cannot be assured of flagging what most needs to be flagged—products whose performance would be of an extremely toxic nature. Yes, we can utilize the available chemical means of analysis, but they are capable only of quantitating the ordinary combustion products, not ones which are extremely toxic. On the basis of this, the philosophy in the U.S. has been that while animal usage should be minimized as much a possible, any time that a quantitative analysis of fire gas toxicity needs to be performed, it must include an animal component.

A VIABLE STRATEGY FOR TOXICITY

The examination of the above facts revealed that the relative contribution of the toxicity from upholstered furniture items to the fire hazard in the room of fire origin is expected to be very limited. Nonetheless, there are some circumstances where toxicity information will be needed. It is seen that hazards due to extreme toxicity of combustion products are expected to be extraordinarily rare, yet the situation can potentially remain that a highly deleterious product could be suggested for the marketplace. The sound engineering strategy for dealing with this issue is, then, seen to be the following:

- Standardize a test for the measurement of toxic potency. This test must contain an animal component if it is to provide any data of utility to this purpose. The radiant toxicity test method is available for this use.

- Define suitable procedures for making a fire hazard analysis using such toxicity test data. Note that the fire hazard analysis will involve a determination of such quantities as the product's HRR, not just the toxic potency.

- Leave up to the authority having jurisdiction the discretion of when such toxicity testing would be mandated. This would, presumably, occur only when there was some evidence suggesting that a certain product might indeed be one of those very rare ones for which extreme toxic potency is an issue.

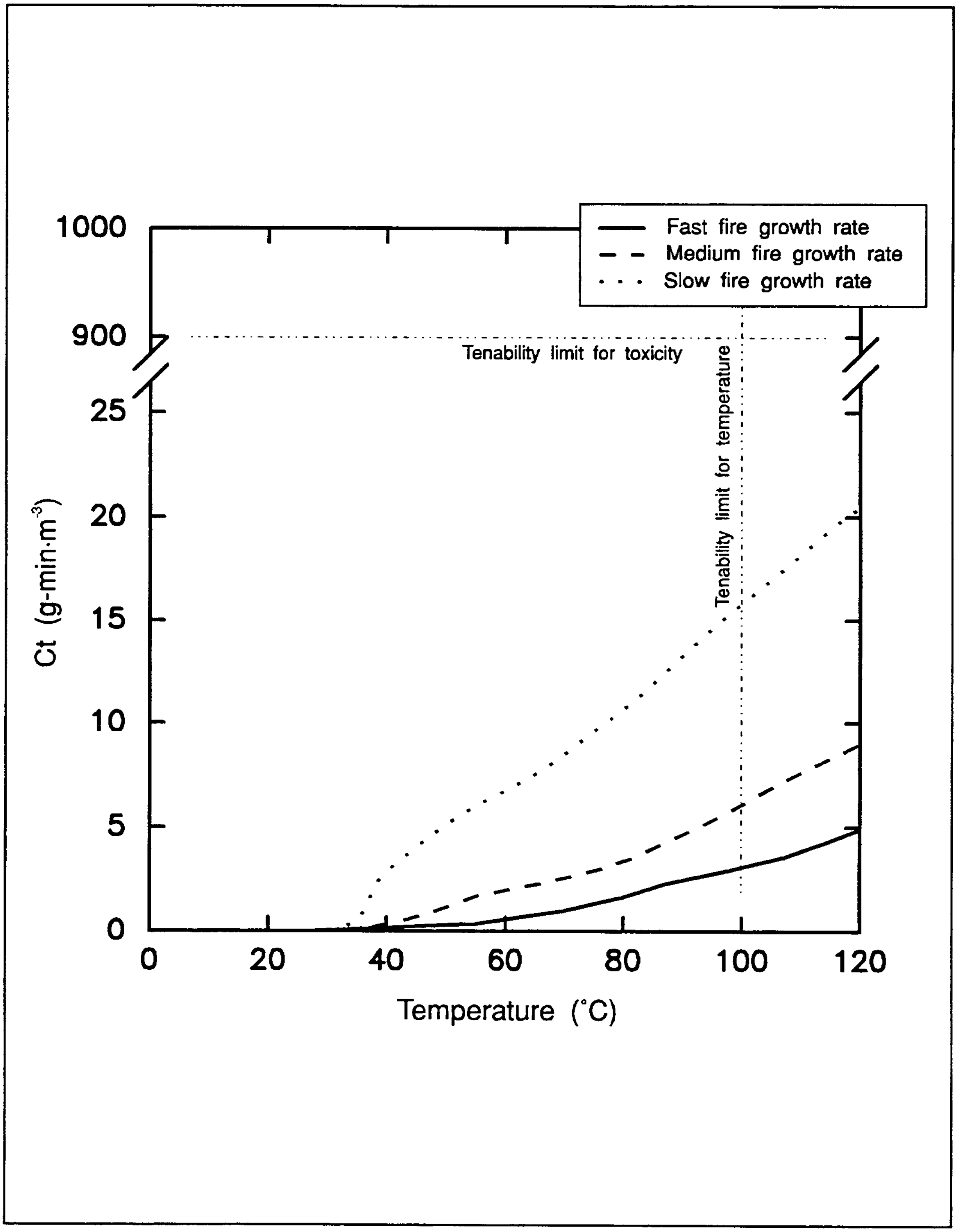

Figure 2 Relative impact of toxicity and thermal effects in the room of fire origin for a range of fire growth rates.

of course, highly dependent on national traits, *e.g.*, whether it is customary or not to keep doors closed within the dwelling unit. Even within Europe, it is entirely likely that a similar study would show distinct regional or national differences.

For completeness of discussion here, we note that *heat is lost as distance away from a fire increases, but toxic combustion products are not.* Thus, occupants who die far away from a fire would most likely die due to toxic gas inhalation alone, without thermal untenability being reached at their location. For occupants to die far away from the source of the fire, the initial fire has to have become quite large, generally attaining flashover within the original room. Toxicity issues when flashover has occurred are complicated by a need to properly account for the dependence of CO production upon available air supply, which starts having a significant effect near the time of flashover. This phenomenon is outside of the scope here, but has recently been treated systematically [9].

THE RELATIVE CONTRIBUTION TO HAZARD OF HRR AND OF TOXICITY

We have seen above that, within the room of fire origin, the effects of HRR on creating lethal occupant conditions are preponderant; other factors are contributory, at best. The situation can now be examined from a different point of view, that of the manufacturer of upholstered furniture. A question he might ask is: "What are my options—can I increase life safety more readily by decreasing the HRR of the product or by reducing its toxic effects (raising the LC_{50} value)?" This is a very reasonable question, and data are available to answer it.

In NIST tests, the worst-performing item of upholstered furniture showed a full-scale peak HRR value of 3120 kW [10]. The best-performing item measured 25 to 31 kW [11], which we can round to 30 kW. Thus, the range of product performance seen for actual, commercial products is slightly over 100:1.

A similar comparison of toxicity values, expressed as 'raw' LC_{50} values, can be cited from experimental NIST toxicity studies [5][c]. These values are for miscellaneous products including, but not limited to, upholstered furniture materials, and they go from 13 to 56 $g \cdot m^{-3}$. This is a range of 4:1.

The relative rankings are illustrated in Fig. 3. The point is quite clear: It is feasible to vary product HRR values over a very wide performance range. Variations in the toxicity are innately limited to a much narrower range. Thus, if a manufacturer chooses to improve the fire safety performance of his product, the possible improvement for HRR can be much greater than could be seen by trying to improve the LC_{50}. The manufacturer still has the responsibility to avoid products which produce unusual toxic effects or extreme toxic potency.

TOXICITY TESTING

During a period of several years' work at NIST, a bench-scale test method for determining the toxic potencies of products and materials was developed [5]. This method solves many of the combustion and toxicological problems plaguing earlier test methods. This method is known as the 'radiant toxicity test method,' sometimes also referred to as the 'NIST/SwRI' method in view of the cooperative work between NIST and the Southwest Research Institute leading to its development.

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c To properly account for CO production in post-flashover fires, a special procedure is used whereby the 'raw' LC_{50} values are corrected for the CO production conditions pertinent to the post-flashover fires. The correction procedure is described in the above reference, but is not pertinent to the present issue of fire safety within the room of initial fire origin; here, the 'raw' values alone suffice.

CONCLUSIONS

Engineering analysis of actual product performance has been used to show that:

- Life safety can be promoted most effectively by ensuring that furniture fires do not reach a high heat release rate.
- Differences among commercial products associated with toxicity effects are very small compared to differences in their heat release rates.
- A standardized combustion toxicity test is needed for use in those rare instances where the combustion product toxicity of upholstered furniture does need to be quantified. A method suitable for this use has already been developed.
- No non-animal-based test is available which can successfully identify products of unusual or extreme toxicity.

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